

FLUOROSULFATE-BASED ELECTRODE ACTIVE MATERIALS

AND METHOD OF MAKING THE SAME

5

FIELD OF THE INVENTION

This invention relates to improved fluorosulfate-based electrode active materials, methods for making such improved active materials, and electrochemical cells employing such improved active materials.

10

BACKGROUND OF THE INVENTION

A battery consists of one or more electrochemical cells, wherein each cell typically includes a positive electrode, a negative electrode, and an electrolyte or other material for facilitating movement of ionic charge carriers between the negative electrode and positive electrode. As the cell is charged, cations migrate from the positive electrode to the electrolyte and, concurrently, from the electrolyte to the negative electrode. During discharge, cations migrate from the negative electrode to the electrolyte and, concurrently, from the electrolyte to the positive electrode.

Such batteries generally include an electrochemically active material having a crystal lattice structure or framework from which ions can be extracted and subsequently reinserted, and/or permit ions to be inserted or intercalated and subsequently extracted.

In general, positive electrode active materials should exhibit a high free energy of reaction with the cation (e.g. Li^+ , Na^+ , and the like), be able to release and

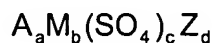
insert a large quantity of cations, maintain its lattice structure upon insertion and extraction of cations, allow rapid diffusion of cations, afford good electrical conductivity, be not significantly soluble in the electrolyte system of the battery, and be readily and economically produced.

5 Unfortunately, many existing electrode materials are not economical to produce, afford insufficient voltage, have insufficient charge capacity, or lose their ability to be recharged over multiple cycles. Therefore, there is a current need for an electrode active material that exhibits greater charge capacity, is economical to produce, affords sufficient voltage, and retains capacity over multiple cycles.

10

SUMMARY OF THE INVENTION

The present invention provides novel electrode materials represented by the nominal general formula:



15 wherein:

- (i) A is at least one alkali metal, and $0 < a \leq 9$;
- (ii) M is at least one redox active element, and $1 \leq b \leq 4$;
- (iii) $1 \leq c \leq 3$; and
- (iv) Z is OH, a halogen, or mixtures thereof, and $0 < d \leq 5$;

20 wherein A, M, Z, a, b, c and d are selected so as to maintain electroneutrality of the material.

This invention also provides electrodes which utilize the electrode active material of this invention. Also provided are batteries that include a first electrode

having an electrode active material of this invention; a second electrode having a compatible active material; and an electrolyte. In one embodiment, the novel electrode material of this invention is used as a positive electrode (cathode) active material, reversibly cycling alkali metal ions with a compatible negative electrode
5 (anode) active material.

DETAILED DESCRIPTION OF THE PREFERRED EMBODIMENTS

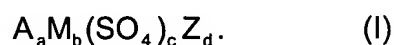
It has been found that the novel electrode materials, electrodes, and batteries of this invention afford benefits over such materials and devices among those known
10 in the art. Such benefits include one or more of increased capacity, enhanced cycling capability, enhanced reversibility, enhanced ionic conductivity, enhanced electrical conductivity, and reduced costs. Specific benefits and embodiments of the present invention are apparent from the detailed description set forth herein below. It should be understood, however, that the detailed description and specific
15 examples, while indicating embodiments among those preferred, are intended for purposes of illustration only and are not intended to limit the scope of the invention.

The present invention provides electrode active materials for use in an electricity-producing electrochemical cell. Each electrochemical cell includes a positive electrode, a negative electrode, and an electrolyte in ion-transfer
20 communication with both the positive and the negative electrode, for transferring ionic charge carriers there between. A "battery" refers to a device having one or more electricity-producing electrochemical cells. Two or more electrochemical cells may be combined, or "stacked," so as to create a multi-cell battery.

The electrode active materials of this invention may be used in the negative electrode, the positive electrode, or both. Preferably, the active materials of this invention are used in the positive electrode. As used herein, the terms "negative electrode" and "positive electrode" refer to the electrodes at which oxidation and reduction occur, respectively, during battery discharge; during charging of the battery, the sites of oxidation and reduction are reversed.

Electrode Active Materials of the Present Invention:

The present invention is directed to novel electrode active materials represented by the following nominal general formula (I):



The term "nominal general formula" refers to the fact that the relative proportion of atomic species may vary slightly on the order of 2 percent to 5 percent, or more typically, 1 percent to 3 percent. The composition of A, M and Z of general formulas (I) through (III) herein, as well as the stoichiometric values of the elements of the active material, are selected so as to maintain electroneutrality of the electrode active material. The stoichiometric values of one or more elements of the composition may take on non-integer values.

For all embodiments described herein, unless otherwise specified, moiety A is selected from the group consisting of elements or alkali metals from Group I of the Periodic Table, and mixtures thereof. As referred to herein, "Group" refers to the Group numbers (i.e., columns) of the Periodic Table as defined in the current IUPAC Periodic Table. See, e.g., U.S. Patent 6,136,472, Barker et al., issued October 24,

2000, incorporated by reference herein. In one embodiment, A is selected from the group consisting of Li (Lithium), Na (Sodium), K (Potassium), and mixtures thereof. A may be a mixture of Li with Na, a mixture of Li with K, or a mixture of Li, Na and K. In another embodiment, A is Na, or a mixture of Na with K. In one preferred
5 embodiment, A is Li.

As used herein, the recitation of a genus of elements, materials or other components, from which an individual component or mixture of components can be selected, is intended to include all possible sub-generic combinations of the listed components, and mixtures thereof. In addition, the words "preferred" and
10 "preferably" refer to embodiments of the invention that afford certain benefits, under certain circumstances. However, other embodiments may also be preferred, under the same or other circumstances. Furthermore, the recitation of one or more preferred embodiments does not imply that other embodiments are not useful and is not intended to exclude other embodiments from the scope of the invention.

15 Removal of an amount of alkali metal (A) from the electrode active material is accompanied by a change in oxidation state of at least one of the "redox active" elements in the active material, as defined herein below. The amount of redox active material available for oxidation/reduction in the active material determines the amount of alkali metal (A) that may be removed. Such concepts are, in general
20 application, well known in the art, e.g., as disclosed in U.S. Patent 4,477,541, Fraioli, issued October 16, 1984; and U.S. Patent 6,136,472, Barker, et al., issued October 24, 2000, both of which are incorporated by reference herein.

A sufficient quantity of alkali metal (A) should be present so as to allow all of the "redox active" elements of M (as defined herein below) to undergo oxidation/reduction. In one embodiment, $0 < a \leq 9$. In another embodiment, $0 < a \leq 1$. In yet another embodiment, $0 < a \leq 3$. In another embodiment, $3 < a \leq 5$. Unless
5 otherwise specified, a variable described herein algebraically as equal to ("="), less than or equal to (" \leq "), or greater than or equal to (" \geq ") a number is intended to subsume values or ranges of values about equal or functionally equivalent to said number.

In general, the amount (a) of alkali metal (A) in the active material varies
10 during charge/discharge. Where the active materials of the present invention are synthesized for use in preparing an electrochemical cell in a discharged state, such active materials are characterized by a relatively high value of "a", with a correspondingly low oxidation state of the redox active components of the active material. As the electrochemical cell is charged from its initial uncharged state, an
15 amount (a') of alkali metal (A) is removed from the active material as described above. The resulting structure, containing less alkali metal (i.e., $a - a'$) than in the as-prepared state, and at least one of the redox active components having a higher oxidation state than in the as-prepared state, essentially maintains the original value of c. The active materials of this invention include such materials in their nascent
20 state (i.e., as manufactured prior to inclusion in an electrode) and materials formed during operation of the battery (i.e., by insertion or removal of alkali metal (A)).

In all embodiments described herein, M includes at least one redox active element. As used herein, the term "redox active element" includes those elements

characterized as being capable of undergoing oxidation/reduction to another oxidation state when the electrochemical cell is operating under normal operating conditions. As used herein, the term "normal operating conditions" refers to the intended voltage at which the cell is charged, which, in turn, depends on the materials used to construct the cell.

Redox active elements useful herein with respect to M include, without limitation, elements from Groups 4 through 11 of the Periodic Table, as well as select non-transition metals, including, without limitation, Ti (Titanium), V (Vanadium), Cr (Chromium), Mn (Manganese), Fe (Iron), Co (Cobalt), Ni (Nickel), Cu (Copper), Nb (Niobium), Mo (Molybdenum), Ru (Ruthenium), Rh (Rhodium), Pd (Palladium), Os (Osmium), Ir (Iridium), Pt (Platinum), Au (Gold), Si (Silicon), Sn (Tin), Pb (Lead), and mixtures thereof. As referred to herein, "include," and its variants, is intended to be non-limiting, such that recitation of items in a list is not to the exclusion of other like items that may also be useful in the materials, compositions, devices, and methods of this invention.

In one embodiment, moiety M is a redox active element. In one subembodiment, M is a redox active element selected from the group consisting of Ti^{2+} , V^{2+} , Cr^{2+} , Mn^{2+} , Fe^{2+} , Co^{2+} , Ni^{2+} , Cu^{2+} , Mo^{2+} , Si^{2+} , Sn^{2+} , and Pb^{2+} . In another subembodiment, M is a redox active element selected from the group consisting of Ti^{3+} , V^{3+} , Cr^{3+} , Mn^{3+} , Fe^{3+} , Co^{3+} , Ni^{3+} , Mo^{3+} , and Nb^{3+} .

In another embodiment, moiety M is a mixture of redox active elements or a mixture of at least one redox active element and at least one non-redox active element. As referred to herein, "non-redox active elements" include elements that

are capable of forming stable active materials, and do not undergo oxidation/reduction when the electrode active material is operating under normal operating conditions.

Among the non-redox active elements useful herein include, without
5 limitation, those selected from Group 2 elements, particularly Be (Beryllium), Mg (Magnesium), Ca (Calcium), Sr (Strontium), Ba (Barium); Group 3 elements, particularly Sc (Scandium), Y (Yttrium), and the lanthanides, particularly La (Lanthanum), Ce (Cerium), Pr (Praseodymium), Nd (Neodymium), Sm (Samarium); Group 12 elements, particularly Zn (Zinc) and Cd (Cadmium); Group 13 elements,
10 particularly B (Boron), Al (Aluminum), Ga (Gallium), In (Indium), Tl (Thallium); Group 14 elements, particularly C (Carbon) and Ge (Germanium), Group 15 elements, particularly As (Arsenic), Sb (Antimony), and Bi (Bismuth); Group 16 elements, particularly Te (Tellurium); and mixtures thereof.

In one embodiment, $M = MI_nMII_o$, wherein $0 < o + n \leq 4$ and each of o and n is
15 greater than zero ($0 < o, n$), wherein MI and MII are each independently selected from the group consisting of redox active elements and non-redox active elements, wherein at least one of MI and MII is redox active.

MI may be partially substituted with MII by isocharge or aliovalent substitution, in equal or unequal stoichiometric amounts. "Isocharge substitution" refers to a
20 substitution of one element on a given crystallographic site with an element having the same oxidation state (e.g. substitution of Ca^{2+} with Mg^{2+}). "Aliovalent substitution" refers to a substitution of one element on a given crystallographic site with an element of a different oxidation state (e.g. substitution of Li^+ with Mg^{2+}).

For all embodiments described herein where MI is partially substituted by MII by isocharge substitution, MI may be substituted by an equal stoichiometric amount of MII, whereby $M = MI_{n-o} MII_o$. Where MI is partially substituted by MII by isocharge substitution and the stoichiometric amount of MI is not equal to the amount of MII, 5 whereby $M = MI_{n-o} MII_p$ and $o \neq p$, then the stoichiometric amount of one or more of the other components (e.g. A and Z) in the active material must be adjusted in order to maintain electroneutrality.

For all embodiments described herein where MI is partially substituted by MII by aliovalent substitution and an equal amount of MI is substituted by an equal 10 amount of MII, whereby $M = MI_{n-o} MII_o$, then the stoichiometric amount of one or more of the other components (e.g. A and Z) in the active material must be adjusted in order to maintain electroneutrality. However, MI may be partially substituted by MII by aliovalent substitution by substituting an "oxidatively" equivalent amount of MII for MI, whereby $M = MI_{n-\frac{o}{V^{MI}}} MII_{\frac{o}{V^{MII}}}$, wherein V^{MI} is the oxidation state of MI, and V^{MII} is the 15 oxidation state of MII.

In one subembodiment, MI is selected from the group consisting of Ti, V, Cr, Mn, Fe, Co, Ni, Cu, Mo, Si, Pb, Mo, Nb, and mixtures thereof, and MII is selected from the group consisting of Be, Mg, Ca, Sr, Ba, Sc, Y, Zn, Cd, B, Al, Ga, In, C, Ge, and mixtures thereof. In this subembodiment, MI may be substituted by MII by 20 isocharge substitution or aliovalent substitution.

In another subembodiment, MI is partially substituted by MII by isocharge substitution. In one aspect of this subembodiment, MI is selected from the group

consisting of Ti^{2+} , V^{2+} , Cr^{2+} , Mn^{2+} , Fe^{2+} , Co^{2+} , Ni^{2+} , Cu^{2+} , Mo^{2+} , Si^{2+} , Sn^{2+} , Pb^{2+} , and mixtures thereof, and MII is selected from the group consisting of Be^{2+} , Mg^{2+} , Ca^{2+} , Sr^{2+} , Ba^{2+} , Zn^{2+} , Cd^{2+} , Ge^{2+} , and mixtures thereof. In another aspect of this subembodiment, MI is selected from the group specified immediately above, and MII is selected from the group consisting of Be^{2+} , Mg^{2+} , Ca^{2+} , Sr^{2+} , Ba^{2+} , and mixtures thereof. In another aspect of this subembodiment, MI is selected from the group specified above, and MII is selected from the group consisting of Zn^{2+} , Cd^{2+} , and mixtures thereof. In yet another aspect of this subembodiment, MI is selected from the group consisting of Ti^{3+} , V^{3+} , Cr^{3+} , Mn^{3+} , Fe^{3+} , Co^{3+} , Ni^{3+} , Mo^{3+} , Nb^{3+} , and mixtures thereof, and MII is selected from the group consisting of Sc^{3+} , Y^{3+} , B^{3+} , Al^{3+} , Ga^{3+} , In^{3+} , and mixtures thereof.

In another embodiment, MI is partially substituted by MII by aliovalent substitution. In one aspect of this subembodiment, MI is selected from the group consisting of Ti^{2+} , V^{2+} , Cr^{2+} , Mn^{2+} , Fe^{2+} , Co^{2+} , Ni^{2+} , Cu^{2+} , Mo^{2+} , Si^{2+} , Sn^{2+} , Pb^{2+} , and mixtures thereof, and MII is selected from the group consisting of Sc^{3+} , Y^{3+} , B^{3+} , Al^{3+} , Ga^{3+} , In^{3+} , and mixtures thereof. In another aspect of this subembodiment, MI is a $2+$ oxidation state redox active element selected from the group specified immediately above, and MII is selected from the group consisting of alkali metals, Cu^{1+} , Ag^{1+} and mixtures thereof. In another aspect of this subembodiment, MI is selected from the group consisting of Ti^{3+} , V^{3+} , Cr^{3+} , Mn^{3+} , Fe^{3+} , Co^{3+} , Ni^{3+} , Mo^{3+} , Nb^{3+} , and mixtures thereof, and MII is selected from the group consisting of Be^{2+} , Mg^{2+} , Ca^{2+} , Sr^{2+} , Ba^{2+} , Zn^{2+} , Cd^{2+} , Ge^{2+} , and mixtures thereof. In another aspect of this subembodiment, MI is a $3+$ oxidation state redox active element selected from

the group specified immediately above, and MII is selected from the group consisting of alkali metals, Cu^{1+} , Ag^{1+} and mixtures thereof.

In another embodiment, $M = M1_q M2_r M3_s$, wherein:

- (a) M1 is a redox active element with a 2+ oxidation state;
- 5 (b) M2 is selected from the group consisting of redox and non-redox active elements with a 1+ oxidation state;
- (c) M3 is selected from the group consisting of redox and non-redox active elements with a 3+ oxidation state; and
- (d) at least one of p, q and r is greater than 0, and at least one of M1, M2, 10 and M3 is redox active. Preferably, each of p, q and r is greater than 0 ($0 < p, q, r$).

In one subembodiment, M1 is substituted by an equal amount of M2 and/or M3, whereby $q = q - (r + s)$. In this subembodiment, then the stoichiometric amount of one or more of the other components (e.g. A and Z) in the active material must be adjusted in order to maintain electroneutrality.

- 15 In another subembodiment, M1 is substituted by an "oxidatively" equivalent amount of M2 and/or M3, whereby $M = M1^{\frac{r}{V^{M1}} - \frac{s}{V^{M1}}} M2^{\frac{r}{V^{M2}}} M3^{\frac{s}{V^{M3}}}$, wherein V^{M1} is the oxidation state of M1, V^{M2} is the oxidation state of M2, and V^{M3} is the oxidation state of M3.

- 20 In one subembodiment, M1 is selected from the group consisting of Ti^{2+} , V^{2+} , Cr^{2+} , Mn^{2+} , Fe^{2+} , Co^{2+} , Ni^{2+} , Cu^{2+} , Mo^{2+} , Si^{2+} , Sn^{2+} , Pb^{2+} , and mixtures thereof; M2 is selected from the group consisting of alkali metals, Cu^{1+} , Ag^{1+} and mixtures thereof; and M3 is selected from the group consisting of Ti^{3+} , V^{3+} , Cr^{3+} , Mn^{3+} , Fe^{3+} , Co^{3+} , Ni^{3+} ,

Mo³⁺, Nb³⁺, and mixtures thereof. In another subembodiment, M1 and M3 are selected from their respective preceding groups, and M2 is selected from the group consisting of Li¹⁺, K¹⁺, Na¹⁺, Ru¹⁺, Cs¹⁺, and mixtures thereof.

In another subembodiment, M1 is selected from the group consisting of Be²⁺, Mg²⁺, Ca²⁺, Sr²⁺, Ba²⁺, Zn²⁺, Cd²⁺, Ge²⁺, and mixtures thereof; M2 is selected from the group consisting of alkali metals, Cu¹⁺, Ag¹⁺, and mixtures thereof; and M3 is selected from the group consisting of Ti³⁺, V³⁺, Cr³⁺, Mn³⁺, Fe³⁺, Co³⁺, Ni³⁺, Mo³⁺, Nb³⁺, and mixtures thereof. In another subembodiment, M1 and M3 are selected from their respective preceding groups, and M2 is selected from the group consisting of Li¹⁺, K¹⁺, Na¹⁺, Ru¹⁺, Cs¹⁺, and mixtures thereof.

In another subembodiment, M1 is selected from the group consisting of Ti²⁺, V²⁺, Cr²⁺, Mn²⁺, Fe²⁺, Co²⁺, Ni²⁺, Cu²⁺, Mo²⁺, Si²⁺, Sn²⁺, Pb²⁺, and mixtures thereof; M2 is selected from the group consisting of alkali metals, Cu¹⁺, Ag¹⁺, and mixtures thereof; and M3 is selected from the group consisting of Sc³⁺, Y³⁺, B³⁺, Al³⁺, Ga³⁺, In³⁺, and mixtures thereof. In another subembodiment, M1 and M3 are selected from their respective preceding groups, and M2 is selected from the group consisting of Li¹⁺, K¹⁺, Na¹⁺, Ru¹⁺, Cs¹⁺, and mixtures thereof.

In one embodiment of the present invention, c = 1. In another embodiment of the present invention, c = 3.

In all embodiments described herein, unless otherwise specified, moiety Z is selected from the group consisting of OH (Hydroxyl), a halogen, and mixtures thereof. In one embodiment, Z is selected from the group consisting of OH (Hydroxyl), F (Fluorine), Cl (Chlorine), Br (Bromine), and mixtures thereof. In

another embodiment, Z is OH. In another embodiment, Z is F, or a mixture of F with OH, Cl, or Br.

In one particular embodiment, the electrode active material is represented by the nominal general formula (II):

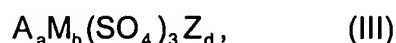


wherein:

- (a) the moieties A, M and Z are as defined herein above;
- (b) $0 < a \leq 2$; $0 < m \leq 2$, and $0 < d \leq 1$; and
- (c) the components of the moieties A, M and Z, as well as the values for a,
10 b and d, are selected so as to maintain electroneutrality of the compound.

In one particular subembodiment, A of general formula (II) is Li, and M includes a 2+ oxidation state redox active element selected from the group consisting of Ti^{2+} , V^{2+} , Cr^{2+} , Mn^{2+} , Fe^{2+} , Co^{2+} , Ni^{2+} , Cu^{2+} , Mo^{2+} , Si^{2+} , Sn^{2+} , and Pb^{2+} (preferably Fe^{2+}).

- 15 In another particular embodiment, the electrode active material is represented by the nominal general formula (III):



wherein:

- (a) the moieties A, M and Z are as defined herein above;
- (b) $0 < a \leq 5$; $1 < m \leq 3$, and $0 < d \leq 4$; and
- (c) the components of the moieties A, M and Z, as well as the values for a,
20 b and d, are selected so as to maintain electroneutrality of the compound.

In one particular subembodiment, A of general formula (III) is Li, and M includes a 3+ oxidation state redox active element selected from the group consisting of Ti^{3+} , V^{3+} , Cr^{3+} , Mn^{3+} , Fe^{3+} , Co^{3+} , Ni^{3+} , Mo^{3+} , Nb^{3+} , and mixtures thereof (preferably V^{3+}).

5

Methods of Manufacture:

The particular starting materials employed will depend on the particular active material to be synthesized, reaction method employed, and desired by-products. The compounds of the present invention are synthesized by reacting at least one A-
10 containing compound, one or more M-containing compounds, at least one SO_4 -containing compound, and one or more Z-containing compounds, at a temperature and for a time sufficient to form the desired reaction product. As used herein, the term "containing" includes compounds which contain the particular component, or react to form the particular component so specified.

15 Sources of alkali metal include any of a number of alkali metal-containing salts or ionic compounds. Lithium, sodium, and potassium compounds are preferred, with lithium being particularly preferred. A wide range of such materials is well known in the field of inorganic chemistry. Examples include the alkali metal-containing fluorides, chlorides, bromides, iodides, nitrates, nitrites, sulfates,
20 hydrogen sulfates, sulfites, bisulfites, carbonates, bicarbonates, borates, phosphates, silicates, antimonates, arsenates, germanates, oxides, acetates, oxalates, and the like. Hydrates of the above compounds may also be used, as well

as mixtures thereof. The mixtures may contain more than one alkali metal so that a mixed alkali metal active material will be produced in the reaction.

Sources of M include, without limitation, M-containing fluorides, chlorides, bromides, iodides, nitrates, nitrites, sulfates, hydrogen sulfates, sulfites, bisulfites, carbonates, bicarbonates, borates, phosphates, hydrogen ammonium phosphates, dihydrogen ammonium phosphates, silicates, antimonates, arsenates, germanates, oxides, hydroxides, acetates, and oxalates of the same. Hydrates may also be used. M in the starting material may have any oxidation state, depending on the oxidation state required in the desired product and the oxidizing or reducing conditions contemplated, if any.

Sulfate compounds that can be used to synthesize the active material include alkali metal and transition metal sulfates and bisulfates as well as mixed metal sulfates such as $(\text{NH}_4)_2\text{Fe}(\text{SO}_4)_2$, $\text{NH}_4\text{Fe}(\text{SO}_4)_2$, and the like.

As noted above, the active materials of the present invention contain a mixture of A, M, SO_4 , and Z. A starting material may provide more than one of these components, as is evident in the list above. In various embodiments of the invention, starting materials are provided that combine, for example, M and SO_4 , thus requiring only the alkali metal and Z to be added. In one embodiment, a starting material is provided that contains A, M and SO_4 . As a general rule, there is sufficient flexibility to allow selection of starting materials containing any of the components of A, M, SO_4 , and Z, depending on availability. Combinations of starting materials providing each of the components may also be used.

In general, any counterion may be combined with A, M, SO₄, and Z. It is preferred, however, to select starting materials with counterions that give rise to the formation of volatile by-products during the reaction. Thus, it is desirable to choose ammonium salts, carbonates, bicarbonates, oxides, hydroxides, and the like, where possible. Starting materials with these counterions tend to form volatile by-products such as water, ammonia, and carbon dioxide, which can be readily removed from the reaction mixture. Nitrogen-containing anions such as nitrate and nitrite also tend to give volatile NO_x by-products.

Additionally, in some cases the performance of the active material may be dependent upon the amount of each reactant present in the reaction mixture. This is because the presence of certain unreacted starting materials in the active material may have a detrimental effect on the electrochemical performance of the active material. One with ordinary skill in the art would readily be able to optimize the electrochemical performance of the active material synthesized by choosing one of the reactants to be the limiting reagent, taking into account any impurities present in the reaction mixture, and comparing the electrochemical performance of the resulting active material to similar active materials wherein alternate reactants are chosen to be the limiting reagent.

One method for preparing the active materials of the present invention is via the hydrothermal treatment of the requisite starting materials. In a hydrothermal reaction, the starting materials are mixed with a small amount of a liquid (e.g. water), and heated in a pressurized vessel or bomb at a temperature that is relatively lower as compared to the temperature necessary to produce the active material in an oven

at ambient pressure. Preferably, the reaction is carried out at a temperature of about 150°C to about 450°C, under pressure, for a period of about 4 to about 48 hours, or until a reaction product forms.

5 A "sol-gel" preparation method may also be employed. Using this method, solute precursors with the required components are mixed in solution and then transformed into a solid via precipitation or gelation. The resulting wet powder or gel is dried at about 100°C to about 400°C for about 1 hour to about 4 hours, optionally, heated up to about 450°C to about 700°C for an additional 1 hour to about 4 hours.

10 Another method for synthesizing the active materials of the present invention is via a thermite reaction, wherein M is reduced by a granular or powdered metal present in the reaction mixture.

The active materials of the present invention can also be synthesized via a solid state reaction, with or without simultaneous oxidation or reduction of M, by heating the requisite starting materials at an elevated temperature for a given period
15 of time, until the desired reaction product forms.

The starting materials are provided in powder or particulate form, and are mixed together by any of a variety of procedures, such as by ball milling, blending in a mortar and pestle, and the like. Typically, the starting materials are ball milled for 12-18 hours, rolling at a rate of 20 rpm. Thereafter the mixture of powdered starting
20 materials may be compressed into a pellet and/or held together with a binder material (which may also serve as a source of reducing agent) to form a closely cohering reaction mixture. The reaction mixture is heated in an oven, generally at a temperature of about 300°C or greater, until a reaction product forms.

The reaction may be carried out under reducing or oxidizing conditions. Reducing conditions may be provided by performing the reaction in a "reducing atmosphere" such as hydrogen, ammonia, carbon monoxide, methane, or mixtures thereof, or other suitable reducing gas. Alternatively or in addition thereto, the
5 reduction may be carried out *in situ* by including in the reaction mixture a reductant that will participate in the reaction to reduce M to a lower oxidation state, and produce by-products that will not interfere with the active material when later used in an electrode or an electrochemical cell.

In one embodiment, the reductant is elemental carbon, wherein reduction is
10 accomplished via simultaneous oxidation of carbon to carbon monoxide and/or carbon dioxide. An excess of carbon, remaining after the reaction, is intimately mixed with the product active material and functions as a conductive constituent in the ultimate electrode formulation. Accordingly, excess carbon, on the order of 100% or greater, may be used. The presence of carbon particles in the starting
15 materials also provides nucleation sites for the production of the product crystals.

The source of reducing carbon may also be provided by an organic material that forms a carbon-rich decomposition product, referred to herein as a "carbonaceous material," and other by-products upon heating under the conditions of the reaction. At least a portion of the organic precursor, carbonaceous material
20 and/or by-products formed by decomposition functions as a reductant during the synthesis reaction, before, during and/or after the organic precursor undergoes thermal decomposition. Such precursors include any liquid or solid organic material (e.g. sugars and other carbohydrates, including derivatives and polymers thereof).

Although the reaction may be carried out in the presence of oxygen, the reaction is preferably conducted under an essentially non-oxidizing atmosphere so as not to interfere with the reduction reactions taking place. An essentially non-oxidizing atmosphere can be achieved through the use of a vacuum, or through the
5 use of inert gases such as argon, nitrogen, and the like.

Preferably, the particulate starting materials are heated to a temperature below the melting point of the starting materials. The temperature should be about 300°C or greater, and desirably about 450°C or greater. CO and/or CO₂ gas evolves during the reaction. Higher temperatures favor CO formation. Some of the
10 reactions are more desirably conducted at temperatures greater than about 600°C; most desirably greater than about 650°C. Suitable ranges for many reactions are from about 700°C to about 950°C.

At about 700°C both the $C \rightarrow CO$ and the $C \rightarrow CO_2$ reactions are occurring. At closer to about 600°C the $C \rightarrow CO_2$ reaction is the dominant reaction. At closer to
15 about 800°C the $C \rightarrow CO$ reaction is dominant. Since the reducing effect of the $C \rightarrow CO_2$ reaction is greater, the result is that less carbon is needed per atomic unit of M to be reduced.

The starting materials may be heated at ramp rates from a fraction of a degree up to about 10°C per minute. In some cases, for example where
20 continuously heated rotary furnaces are employed, the ramp rate may be significantly higher. Once the desired reaction temperature is attained, the reactants (starting materials) are held at the reaction temperature for a time sufficient for the

reaction to occur. Typically the reaction is carried out for several hours at the final reaction temperature.

After the reaction is complete, the products are preferably cooled from the elevated temperature to ambient (room) temperature (i.e., about 10°C to about 5 40°C). It is also possible to quench the products to achieve a higher cooling rate, for example on the order of about 100°C/minute. The thermodynamic considerations such as ease of reduction of the selected starting materials, the reaction kinetics, and the melting point of the reactants will cause adjustment in the general procedure, such as the amount of reducing agent, the temperature of the 10 reaction, and the dwell time.

Electrochemical Cells:

To form an electrode, the active material of the present invention may be combined with a polymeric binder (e.g. polyvinylidene difluoride (PVdF) and 15 hexafluoropropylene (HFP)) in order to form a cohesive mixture. The mixture is then placed in electrical communication with a current collector which, in turn, provides electrical communication between the electrode and an external load. The mixture may be formed or laminated onto the current collector, or an electrode film may be formed from the mixture wherein the current collector is embedded in the 20 film. Suitable current collectors include reticulated or foiled metals (e.g. aluminum, copper and the like). An electrically conductive diluent or agent (e.g. a carbon such as carbon black and the like) may be added to the mixture so as to increase the electrical conductivity of the electrode. In one embodiment, the electrode material is

pressed onto or about the current collector, thus eliminating the need for the polymeric binder. In one embodiment, the electrode contains 5 to 30% by weight electrically conductive agent, 3 to 20% by weight binder, and the remainder being the electrode active material.

5 To form an electrochemical cell, a solid electrolyte or an electrolyte-permeable separator is interposed between the electrode and a counter-electrode. In one embodiment, the electrolyte contains a solvent selected from the group consisting of the electrolyte comprises a lithium salt and a solvent selected from the group consisting of dimethyl carbonate (DMC), diethylcarbonate (DEC),
10 dipropylcarbonate (DPC), ethylmethylcarbonate (EMC), ethylene carbonate (EC), propylene carbonate (PC), butylene carbonate, lactones, esters, glymes, sulfoxides, sulfolanes, and mixtures thereof; and 5 to 65% by weight of an alkali metal salt. Preferred solvent combinations include EC/DMC, EC/DEC, EC/DPC and EC/EMC. In one embodiment, the counter-electrode contains an intercalation active material
15 selected from the group consisting of a transition metal oxide, a metal chalcogenide, carbon (e.g. graphite), and mixtures thereof. Counter electrodes, electrolyte compositions, and methods for making the same, among those useful herein, are described in U.S. Patent 5,700,298, Shi et al., issued December 23, 1997; U.S. Patent 5,830,602, Barker et al., issued November 3, 1998; U.S. Patent 5,418,091,
20 Gozdz et al., issued May 23, 1995; U.S. Patent 5,508,130, Golovin, issued April 16, 1996; U.S. Patent 5,541,020, Golovin et al., issued July 30, 1996; U.S. Patent 5,620,810, Golovin et al., issued April 15, 1997; U.S. Patent 5,643,695, Barker et al., issued July 1, 1997; U.S. Patent 5,712,059, Barker et al., issued January 27,

1997; U.S. Patent 5,851,504, Barker et al., issued December 22, 1998; U.S. Patent 6,020,087, Gao, issued February 1, 2001; and U.S. Patent 6,103,419, Saidi et al., issued August 15, 2000; all of which are incorporated by reference herein.

Electrochemical cells composed of electrodes (including polymer-type
5 stacked cells and cylindrical-type cells), electrolytes and other materials, among those useful herein, are described in the following documents, all of which are incorporated by reference herein: U.S. Patent 4,668,595, Yoshino et al., issued May 26, 1987; U.S. Patent 4,792,504, Schwab et al., issued December 20, 1988; U.S. Patent 4,830,939, Lee et al., issued May 16, 1989; U.S. Patent 4,935,317, Fauteaux
10 et al., issued June 19, 1980; U.S. Patent 4,990,413, Lee et al., issued February 5, 1991; U.S. Patent 5,037,712, Shackle et al., issued August 6, 1991; U.S. Patent 5,262,253, Golovin, issued November 16, 1993; U.S. Patent 5,300,373, Shackle, issued April 5, 1994; U.S. Patent 5,399,447, Chaloner-Gill, et al., issued March 21, 1995; U.S. Patent 5,411,820, Chaloner-Gill, issued May 2, 1995; U.S. Patent
15 5,435,054, Tonder et al., issued July 25, 1995; U.S. Patent 5,463,179, Chaloner-Gill et al., issued October 31, 1995; U.S. Patent 5,482,795, Chaloner-Gill., issued January 9, 1996; U.S. Patent 5,660,948, Barker, issued September 16, 1995; U.S. Patent No. 5,869,208, Miyasaka, issued February 9, 1999; U.S. Patent No. 5,882,821, Miyasaka, issued March 16, 1999; U.S. Patent No. 5,616,436, Sonobe.
20 et al., issued April 1, 1997; and U.S. Patent 6,306,215, Larkin, issued October 23, 2001.

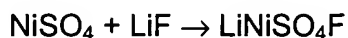
The following non-limiting examples illustrate the compositions and methods of the present invention.

EXAMPLE 1

An electrode active material having the formula LiNiSO_4F is made as follows.

The following starting materials are provided, and the reaction proceeds as follows.

5



The reactants are pre-mixed according to the following proportions:

| | | |
|----|--|--------|
| | 0.02 moles NiSO_4 (mol. wt. = 154.75 g/mol) | 2.57 g |
| 10 | 0.02 moles LiF (25.94 g/mol) | 0.43 g |

The above starting materials are combined and ball milled to mix the particles. Thereafter, the particle mixture is pelletized. The pelletized mixture is heated, preferably in a flowing inert atmosphere (e.g. argon), until a reaction product
15 forms. The sample is removed from the oven and cooled. A first sample synthesized by this method (12 hour dwell time ramped at 2°C per minute to 600°C) yielded a soft yellow/green/white pellet with inconsistent uniformity. A second sample synthesized by this method (30 minute dwell time at 600°C in air) yielded a hard yellow pellet with good uniformity.

EXAMPLE 2

An electrode active material having the formula LiFeSO_4F is made as follows.

The following starting materials are provided, and the reaction proceeds as follows.



The reactants are pre-mixed according to the following proportions:

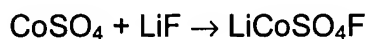
| | | |
|---|--|--------|
| 5 | 0.01 moles FeSO_4 (dry) (mol. wt. = 151.91 g/mol) | 1.71 g |
| | 0.01 moles LiF (25.94 g/mol) | 0.29 g |

The above-noted mixture is subjected to the reaction conditions specified in Example 1 to form the LiFeSO_4F active material. A first sample synthesized by this method (12 hour dwell time ramped at 2°C per minute to 600°C) yielded a semi-hard red/grey pellet with inconsistent uniformity. A second sample synthesized by this method (15 minute dwell time at 500°C in air) yielded a hard brown/black/red reaction product with good uniformity. A third sample synthesized by this method (15 minute dwell time at 450°C in air) yielded a hard red/grey reaction product with satisfactory uniformity.

EXAMPLE 3

An electrode active material having the formula LiCoSO_4F is made as follows.

20 The following starting materials are provided, and the reaction proceeds as follows.



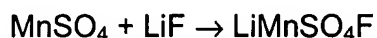
The reactants are pre-mixed according to the following proportions:

| | |
|--|--------|
| 0.02 moles CoSO ₄ (mol. wt. = 154.99 g/mol) | 2.57 g |
| 0.02 moles LiF (25.94 g/mol) | 0.43 g |

The above-noted mixture is subjected to the reaction conditions specified in Example 1 to form the LiCoSO₄F active material. A first sample prepared by this method (15 minute dwell time at 650°C in air) melted. When the reaction was repeated at 500°C in air, the reaction yielded a hard purple pellet with satisfactory uniformity.

10 EXAMPLE 4

An electrode active material having the formula LiMnSO₄F is made as follows. The following starting materials are provided, and the reaction proceeds as follows.



15 The reactants are pre-mixed according to the following proportions:

| | |
|--|--------|
| 0.02 moles MnSO ₄ (mol. wt. = 151.00 g/mol) | 2.56 g |
| 0.02 moles LiF (25.94 g/mol) | 0.44 g |

20 The above-noted mixture is subjected to the reaction conditions specified in Example 1 to form the LiMnSO₄F active material. A first sample synthesized by this method (5 minute dwell time at 650°C in air) melted during heating. A second sample synthesized by this method (15 minute dwell time at 500°C in air) yielded a

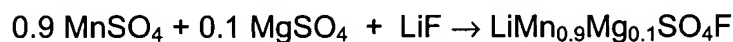
hard light-tan pellet with satisfactory uniformity. A third sample synthesized by this method (1 hour dwell time at 450°C in air) yielded a semi-hard light-tan/peach pellet with good uniformity.

5

EXAMPLE 5

An electrode active material having the formula $\text{LiMn}_{0.9}\text{Mg}_{0.1}\text{SO}_4\text{F}$ is made as follows. The following starting materials are provided, and the reaction proceeds as follows.

10



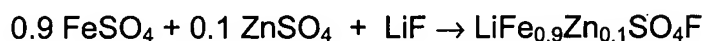
The reactants are pre-mixed according to the following proportions:

| | |
|---|--------|
| 0.015 moles MnSO_4 (mol. wt. = 151.00 g/mol) | 2.31 g |
| 0.002 moles MgSO_4 (120.36 g/mol) | 0.20 g |
| 15 0.020 moles LiF (25.94 g/mol) | 0.44 g |

The above-noted mixture is subjected to the reaction conditions specified in Example 1 to form the $\text{LiMn}_{0.9}\text{Mg}_{0.1}\text{SO}_4\text{F}$ active material. A sample synthesized by this method (15 minute dwell time at 500°C in controlled air) yielded a hard light-tan
20 pellet with satisfactory uniformity.

EXAMPLE 6

An electrode active material having the formula $\text{LiFe}_{0.9}\text{Zn}_{0.1}\text{SO}_4\text{F}$ is made as follows. The following starting materials are provided, and the reaction proceeds as follows.



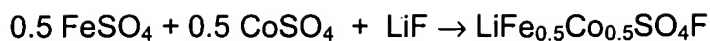
The reactants are pre-mixed according to the following proportions:

| | | |
|----|---|--------|
| 10 | 0.015 moles FeSO_4 (dry) (mol. wt. = 151.91 g/mol) | 2.32 g |
| | 0.002 moles ZnSO_4 (161.44 g/mol) | 0.27 g |
| | 0.020 moles LiF (25.94 g/mol) | 0.44 g |

The above-noted mixture is subjected to the reaction conditions specified in Example 1 to form the $\text{LiMn}_{0.9}\text{Zn}_{0.1}\text{SO}_4\text{F}$ active material. A sample synthesized by this method (15 minute dwell time at 500°C in controlled air) yielded a pellet with satisfactory uniformity.

EXAMPLE 7

20 An electrode active material having the formula $\text{LiFe}_{0.5}\text{Co}_{0.5}\text{SO}_4\text{F}$ is made as follows. The following starting materials are provided, and the reaction proceeds as follows.



The reactants are pre-mixed according to the following proportions:

| | | |
|---|---|--------|
| | 0.008 moles FeSO_4 (dry) (mol. wt. = 151.91 g/mol) | 1.29 g |
| 5 | 0.008 moles CoSO_4 (154.99 g/mol) | 1.32 g |
| | 0.016 moles LiF (25.94 g/mol) | 0.41 g |

The above-noted mixture is subjected to the reaction conditions specified in Example 1 to form the $\text{LiMn}_{0.9}\text{Zn}_{0.1}\text{SO}_4\text{F}$ active material. A sample synthesized by this method (15 minute dwell time at 500°C in controlled air) yielded a pellet with satisfactory uniformity.

EXAMPLE 8

An electrode active material having the formula $\text{Li}_3\text{Fe}_2(\text{SO}_4)_3\text{F}$ is made as follows. The following starting materials are provided, and the reaction proceeds as follows.



The reactants are pre-mixed according to the following proportions:

| | | |
|--|--|--------|
| | 0.02 moles FeSO_4 (dry) (mol. wt. = 151.91 g/mol) | 3.04 g |
| | 0.01 moles Li_2SO_4 (109.94 g/mol) | 1.10 g |
| | 0.01 moles LiF (25.94 g/mol) | 0.26 g |

The above-noted mixture is subjected to the reaction conditions specified in Example 1 to form the $\text{Li}_3\text{Fe}_2(\text{SO}_4)_3\text{F}$ active material. A sample synthesized by this method (15 minute dwell time at 500°C in controlled air) yielded a pellet with satisfactory uniformity.

10

The examples and other embodiments described herein are exemplary and not intended to be limiting in describing the full scope of compositions and methods of this invention. Equivalent changes, modifications and variations of specific embodiments, materials, compositions and methods may be made within the scope of the present invention, with substantially similar results.

15